GNATforLEON / ORK+
User Manual

Version 1.4 — 11 January, 2013

For GNATforLEON 2.3.0/ ORK+
and XtratuM on LEON3 computers

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This manual has been adapted to GNATforLEON from the *Operation Manual for the Open Ravenscar Real-Time Kernel* (ORK). The original software and its associated documentation were developed at UPM under ESA contract No.13863/99/NL/MV.

Status: Final

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The original Operation Manual for ORK was written by Juan A. de la Puente, Juan Zamorano, José F. Ruiz, Ramón Fernández-Marina, and Miguel Ángel Ajo.

History

Version	**Date**	**Comments**
1.0	2007-07-18	First public release.
1.1	2008-11-18	Revised version for GNATforLEON 2.0.1.
1.2	2009-03-30	Revised version with some fixes.
1.3	2009-07-30	New version for GNATforLEON 2.1.0
1.4	2013-01-11	New version for GNATforLEON 2.3.0 for XtratuM/LEON3

Contents

Chapter 1

Introduction

1.1 Intended readership

This manual contains instructions for the use of the *Open Ravenscar real-time Kernel* (ORK+) and the GNATforLEON compilation toolchain with the XtratuM hypervisor. It should be read by application programmers and system administrators of software projects using ORK+ and GNATforLEON.

Prior knowledge of the Ada (ARM05) programming languages and the XtratuM (Masmano et al., 2005) hypervisor is assumed. The reader should also be familiar with the GNAT and GCC programming environments (GNATRM), the GDB debugger (Stallman and Pessch, 2007), and the fundamentals of real-time programming and the Ravenscar profile (ISO/IEC, a).

1.2 Purpose

The purpose of this document is to describe how to use, install, and configure GNATforLEON for the XtratuM hypervisor.

GNATforLEON is an integrated package combining an instance of the GNAT compiler for the SPARC v8 architecture with ORK+, an open-source real-time kernel of reduced size and complexity, for which users can seek certification for mission-critical space applications. The kernel supports Ada 2005 applications on LEON-based computer.

GNATforLEON is fully integrated with other GNAT-based tools and with GDB, the GNU debugger.

1.3 Applicability statement

This manual applies to the following versions of software:

- GNATforLEON 2.3.0/ORK+ 2.3.0
- GNAT GPL 2011
- GCC 4.5
- GDB 7.2

1.4 Compliance to standards

ORK+ supports the tasking model defined in the Ada 2005 standard (ISO/IEC 8652:1995/Amd 1:2007), including appendices C and D, except for the following:

1. The tasking model is restricted as specified by the Ravenscar profile (Ada Reference Manual, D13.1). Consequently,
   - Pragma Priority_Specific_Dispatching is not supported.
   - Only the FIFO_Within_Priorities dispatching policy with the Ceiling_Locking policy is supported.
2. The following exceptions to the Ravenscar profile are supported:
   - At most one statically declared execution-time timer per task is allowed.
   - Statically declared group budgets are allowed.

1.5 Free software

The ORK+ kernel is free software, developed and maintained by UPM , and distributed under the GNU General Public Licence (GPL).

You can also download the latest version of GNATforLEON/ORK+ from the ORK+ web site:

`http://www.dit.upm.es/ork/`

1.6 Related documents

The following documents contain additional information about software tools that can be used to develop real-time software with GNATforLEON:

1. Ada 2005 Reference Manual (ARM05).
2. Ada 2005 Rationale (Barnes, 2008).
3. GNAT Reference Manual (GNATRM).
4. GNAT User's Guide (GNATUG).
5. Using the GNAT Programming Studio (GPSUG)
6. Debugging with GDB (Stallman and Pessch, 2007).

1.7 Problem reporting instructions

If you obtained GNATforLEON from a support organization, we recommend you contact that organization first. You can find contact information for support organizations on the ORK+ web site,

`http://www.dit.upm.es/ork/`

In any event, we also recommend that you send bug reports for GNATforLEON to:

```
ork@dit.upm.es
```

We welcome bug reports, as they are a vital part of the process of the continuing improvement of ORK+. You will help us (and make it more likely that we will look at your report in a timely manner) if you follow these guidelines:

- Please report each bug in a separate message, and add a short but specific subject.

- Please include full sources. We can't duplicate errors without the full sources. Include all sources in the single email message with appropriate indications in the multiple file cases, see below. Also say exactly what you saw, do not assume that we can guess what you saw, or duplicate the behaviour you encountered.

  All sources must be sent in plain ASCII or UTF-8 format.

- Please include a complete identification of the version of the system you are running (i.e. development and target environments, as well as versions of GNATforLEON and all other software you are using).

- Please try to reduce your example to a simple one.

If you think that you have found a bug in GNAT, GCC, or GDB, rather than GNATforLEON or the ORK+ kernel, please send the bug report to the appropriate address:

- GNAT: `report@gnat.com`

- GCC: `bug-gcc@gnu.org`

- GDB: `bug-gdb@gnu.org`

1.8 Glossary

1.8.1 Definitions

Development platform. The computer system (hardware and software) which is used to write, compile, and debug embedded software.

Execution platform. The computer hardware, and possibly basic ROM resident software (such as a bootstrap loader) where the embedded software is executed.

Target platform. The same as the execution platform.

RP program. A program that complies with the Ravenscar profile restrictions.

1.8.2 Acronyms

ALRM	Ada Language Reference Manual.
API	Application Program Interface.
ATCB	Ada Task Control Block.
CCS	Cross Compilation System
DSU	Debug Support Unit.
ESA	European Space Agency.
ESTEC	European Space Research and Technology Center.
FPU	Floating-Point Unit.
FSF	Free Software Foundation.
GDB	GNU Debugger.
GNAT	GNU New York University Ada Translator.
GNARL	GNU Ada Run-Time Library.
GNARLI	GNU Ada Run-Time Library Interface.
GNORT	GNAT No Run Time.
GNU	GNU is Not Unix.
GNULL	GNU Low-Level Library.
GNULLI	GNU Low-Level Library Interface.
GPL	GNU Public License.
GPS	GNAT Programming Studio.
GUI	Graphic User Interface.
HIS	High-Integrity System.
IRTAW	International Real-Time Ada Workshop.
ISO	International Standards Organization.
LGPL	Lesser GNU Public License (formerly Library GPL).
ORK	Open Real-Time Ravenscar Kernel.
OS	Operating System.
PC	IBM Personal Computer architecture.
PROM	Programmable Read-Only Memory.

RAVENSCAR Reliable Ada Verifiable Executive Needed for Scheduling Critical Applications in Real-Time.

RP Ravenscar Profile.

RP program An Ada program that complies with the Ravenscar profile.

RTOS Real-Time Operating System.

UPM Universidad Politécnica de Madrid — Technical University of Madrid.

URL Uniform Resource Locator.

1.9 References

1.9.1 Applicable documents

1. ECCS-E-ST-40C. Space Engineering — Software (ECSS).

2. Ada Reference Manual (ARM05).

3. Guide for the use of the Ada Ravenscar Profile in high integrity systems (ISO/IEC, a).

4. Guidance for the Use of the Ada Programming Language in High Integrity Systems (ISO/IEC, b).

5. XtratuM Hypervisor Reference Manual (Masmano et al., 2011).

1.9.2 Reference documents

1. LEON3 Manuals (LEON3).

2. GRMON User's Manual (Gaisler Research, 2007).

3. Sparc 8 Architecture Manual (SPARCv8).

4. Ada 2005 Rationale (Barnes, 2008)

5. Ada Quality and Style Guide (AQS05).

6. GNAT Manuals (GNATRM; GNATUG).

7. Debugging with GDB (Stallman and Pessch, 2007).

Additional details and references can be found in the bibliography at the end of this volume.

1.10 History

ORK, the first version of the Open Ravenscar real-time Kernel, was developed under ESA/ESTEC contract in the period 1999–2000, with subsequent updates up to 2003. It was targeted to ECR32 computers, based on a SPARC 7 architecture, and was integrated with a custom-crafted version of GNAT 3.13p.

In the period 2003–2005, UPM and AdaCore developed a commercially supported version of the kernel. This version was integrated in the *GNAT Pro for ERC32* product, which is commercialized by AdaCore.

The current version of the kernel, now called ORK+, was developed in the framework of the ASSERT project.[1]

ORK+ has been ported to XtratuM in the framework of this project.

1.11 Contributors

1.11.1 Contributors to ORK

ORK was developed by a team of the Department of Telematics Engineering, Universidad Politécnica de Madrid(DIT/UPM), led by Juan Antonio de la Puente. The other members of the team were Juan Zamorano, José F. Ruiz, Ramón Fernández, and Rodrigo García. Alejandro Alonso and Ángel Álvarez acted as document and code reviewers, and contributed to the technical discussions with many fruitful comments and suggestions. The same team developed the adapted packages that enable GNAT to work with ORK.

GDB was adapted to ORK by Jesús González-Barahona, Vicente Matellán, Andrés Arias, and Juan Manuel Dodero. José Centeno and Pedro de las Heras acted as reviewers for this part of the work. All of them work at the Department of Engineering, Universidad Rey Juan Carlos, Madrid.

The ORK software was validated by Jesús Borruel and Juan Carlos Morcuende, from Construcciones Aeronáuticas (CASA), Space Division.[2] We also relied very much on Andy Wellings and Alan Burns, of the University of York, UK, for reviewing and discussions about the Ravenscar profile and its implementation.

ORK was developed under contract with ESA. Jorge Amador, Tullio Vardanega and Jean-Loup Terraillon provided many positive criticism and contributed the user's view during the development. The project was carried out from September, 1999 to June, 2000.

1.11.2 Contributors to ORK+

ORK+, the real-time kernel used in GNATforLEON, was developed by a team of the Department of Telematics Engineering, Universidad Politécnica de Madrid (DIT/UPM), lead by Juan Antonio de la Puente. The other members of the team were Juan Zamorano, José Pulido, Santiago Urueña, Jorge López, and José Redondo.

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[1]ASSERT (Automated proof-based System and Software Engineering for Real-Time systems) is an Integrated Project partially funded by the European Commission within the Information Society Technologies priority of the 6th Framework Programme in the area *embedded systems*. UPM's work in the project was also supported by the Spanish National R&D Plan.

[2]Currently integrated into EADS-Astrium.

The same team worked in collaboration with AdaCore to port GNAT to LEON2, and to develop the adapted runtime packages that enable GNAT to work with ORK+.

GNATforLEON was developed in the framework of the ASSERT and THREAD projects. It is based on AdaCore GNAT Pro ERC32 product which in turn was based on ORK.

ORK+ was ported to XtratuM by a team of the Department of Telematics Engineering, Universidad Politécnica de Madrid (DIT/UPM), lead by Juan Antonio de la Puente. The other members of the team are Juan Zamorano, Ángel Esquinas, and Daniel Brosnan.

1.12 Document overview

The rest of this document is organised as follows:

- Chapter 2 describes the general structure of the GNATforLEON software and the Ravenscar profile restrictions.
- Chapter 3 contains instructions for writing, compiling, linking, executing, and debugging programs with the GNATforLEON software.
- Chapter 4 describes in detail the functions of GNATforLEON and the way it is linked with Ada programs.
- Appendix A describes the Ravenscar profile in detail.
- Appendix B contains a comprehensive example of a Ravenscar-compliant program and its compilation with GNATforLEON.
- Appendix C contains a copy of the GNU General Public License (GPL).

Chapter 2

Software overview

2.1 The ORK+ kernel

ORK+ (Open Ravenscar Real-Time Kernel) is a small, high performance real-time kernel that provides restricted tasking support for Ada programs.

The kernel is intended to support mission critical real-time software systems. In order to ensure that the software is highly reliable, that, if required, may even be subject to a certification process, program constructs which are not verifiable should not be used. The exact set of language features to be avoided depends on the degree of integrity that is desired for the software and the verification methods that are to be used. A detailed account of the Ada language issues in high integrity systems can be found in the ISO technical report *Guide for the use of the Ada Programming Language in High Integrity Systems* (ISO/IEC, b). Based on these considerations, language subsets for building software with different levels of integrity can be defined. In the case of Ada, there is a standard mechanism to enforce that only the required subset of the language is used by means of the pragma `Restrictions` and the restriction identifiers that are defined in the Ada "Safety and Security" annex (ARM05, Annex H).

Tasking has often been considered not safe for high integrity systems, mainly due to the difficulty of analysing and verifying tasking programs. However, results in response time analysis for fixed priority preemptive scheduling (Burns, 1994) enable limited tasking mechanisms to be used even in this kind of systems.

One of the goals of the 8th International Real-Time Ada Workshop (IRTAW 8), which was held in 1997 in Ravenscar, Yorkshire, England, was to define a safe tasking model for Ada. The outcome of this work is known as the "Ravenscar profile" (Baker and Vardanega, 1997). The profile was slightly modified in the following IRTAW meetings, after some experience was gained on its implementation and use. It was later included in the Ada High-Integrity Systems report (ISO/IEC, b), and it finally made its way into the current Ada 2005 standard (ARM05, Annex D).

The profile defines a subset of Ada tasking that includes static tasks (with no entries) and protected objects (with at most one entry), a real-time clock and `delay until` statements, as well as protected interrupt handler procedures and other tasking-related features. A detailed description can be found in appendix A.

The restrictions in Ada tasking defined in the Ravenscar profile enable tasking to be supported by a small, reliable kernel instead of a full operating systems. ORK+ is one such kernel, which enables critical real-time systems to be executed on a bare

processor with no underlying operating system.

The kernel is integrated with the GNAT compilation system. A special cross-compilation version of GNAT is included in the GNATforLEON distribution. Real-time programs are written in a subset of Ada which is consistent with the Ravenscar profile and with other, non tasking restrictions, as desired according to the degree of integrity that is required for the program. The restrictions can be enforced at compilation time by means of appropriate restriction pragmas.

The code generated by GNATforLEON for XtratuM can be used as a loadable image in an XtratuM partition. Debugging support is available with the GDB version that comes with the GNATforLEON distribution. GNATforLEON can be used from the GNAT Programming Studio (GPS).

2.2 Architecture of ORK+

The kernel consists of the following Ada packages (figure 2.1):

- System.BB:[1] Root package (empty interface).
- System.BB.Threads: Thread management, including synchronization and scheduling control functions.
- System.BB.Threads.Queues: Different kernel queues such as alarm queue and ready queue.
- System.BB.Time: Clock and delay services including support for timing events.
- System.BB.Time.Execution_Time_Support: Execution time clocks and timers as well as group budgets support.
- System.BB.Interrupts: Interrupt handling.
- System.BB.Parameters: Configuration parameters.
- System.BB.CPU_Primitives: Processor-dependent definitions and operations.
- System.BB.Peripherals: Support for peripherals in the target board.
- System.BB.Peripherals.Registers: Definitions related to input-output registers of the peripheral devices.
- System.BB.Serial_Output: Support for serial output to a console.
- System.BB.Xtratum: The interface to XtratuM hypercalls.

The kernel is not intended to be directly used from Ada programs. Instead, an interface to the GNU Ada Runtime Library (GNARL) is used so that Ada tasking constructs can be directly used by the real-time application programmer. This interface is described in the next section.

[1] "BB" stands for "bare-board kernel".

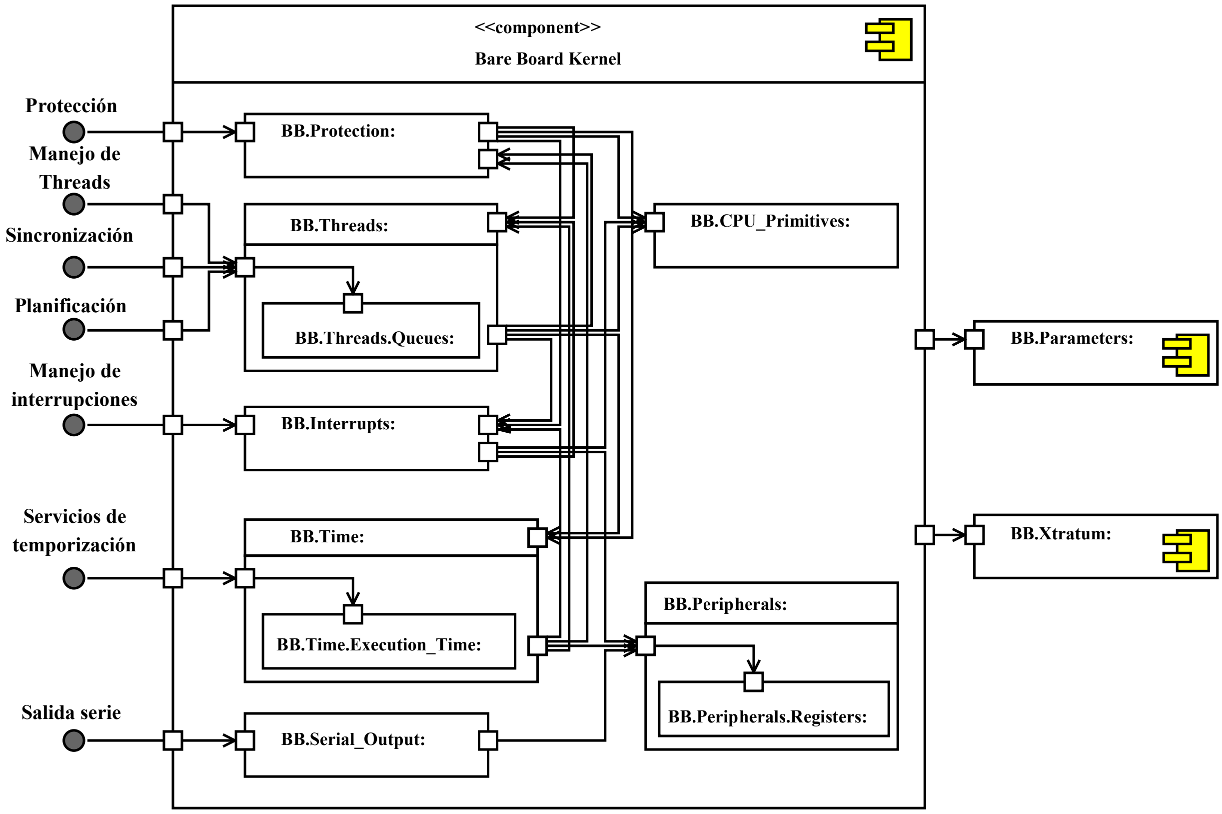

Figure 2.1: Architecture of ORK+

2.3 Interface for Ada programs

Ada tasking is implemented in GNAT by means of the run-time library, called GNARL (Giering and Baker, 1994). The parts of GNARL which are dependent on a particular machine and operating system are known as GNULL, and its interface to the platform-independent part of the GNARL is called GNULLI. The GNATforLEON instance of GNULL is built on top of the bare-board kernel (i.e. ORK+), which provides all the low-level tasking support functionality required by the Ravenscar profile subset of Ada tasking (figure 2.2).

Ravenscar-compliance of Ada programs is enforced by means of the configuration pragma Profile (Ravenscar). GNATforLEON uses a restricted version of GNARL with reduced size and complexity which was developed by AdaCore with certification in mind and just to support the Ravenscar profile. A special version of GNULL is also used, which interfaces directly with the kernel. All this complexity is hidden to the programmer, who only needs to insert the pragma Profile (Ravenscar) in the GNAT configuration file (usually named `gnat.adc`).

2.4 Ada/XtratuM binding

The package System.BB.Xtratum (see figure 2.1) provides the interface to the XtratuM hypercalls that are used by the ORK+ kernel. These include interrupt management, clock management, and SPARC v8 specific hypercalls. In addition to these functions, there are some other XtratuM features that can be used by Ada applications, even

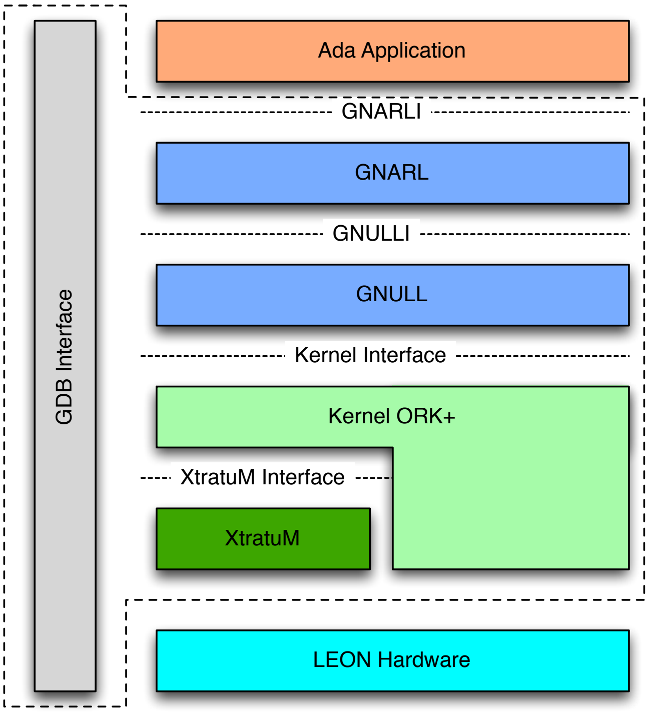

Figure 2.2: Architecture of the GNAT run-time system based on ORK+/XtratuM

though they are not used by the kernel itself. Such features include inter-partition communication and partition management.

Two Ada interface packages have been developed in order to enable Ada partitions to communicate with other partitions, and to enable partition management. Both of them are part of the XtratuM hierarchy as they are intended to be directly used by the Ada partition code: Xtratum.IPC and Xtratum.PM.

In the future, additional interface packages may be developed if Ada partitions need additional XtratuM functionality, such as health monitoring management. Currently, the binding consists of the following Ada packages:

- Xtratum: Root package (empty interface).
- Xtratum.PM: Interfaces to Xtratum partition management hypercalls.
- Xtratum.IPC: Interfaces to Xtratum inter-partition communication hypercalls used for managing queuing and sampling ports.
- Xtratum.Streams: Definition of types to be used with sampling and queuing port messages.

2.5 Hardware and software environment

The GNATforLEON kernel is intended to be used with a GNAT compilation system targeted to a LEON3 computer. In order to use it effectively, the following components are required.

2.5.1 Development platform

Real-time software based on ORK+ can be developed on a PC-compatible system with a GNU/Linux operating system. The software has been tested with the Ubuntu 12.04 distribution of GNU/Linux.

The cross development system consists of the following packages targeted to ELF-32 LEON3:

- GNAT GPL 2011: GNU Ada 2005 compilation system.
- GCC 4.5: GNU C compiler.
- GMP 4.2.2: GNU library for arbitrary precision arithmetic.
- MPC 0.8: GNU library for the arithmetic of complex numbers.
- MPFR 2.3.1: GNU library for multiple-precision floating-point computations.
- GDB 7.2: GNU debugger.
- newlib 1.14: Cygnus C-library.
- binutils 2.16.1: GNU binary utilities.
- ORK+ 2.3.0: ORK+ kernel and GNAT patches.

You can download all the above mentioned packages from `http://www.dit.upm.es/ork/`. Section 4.1 shows how to install a GNATforLEON compilation system from both the binary and source distributions.

You also may find it useful to have the GNAT Programming Studio (GPS) (`https://libre.adacore.com/gps/`) for developing applications with GNATforLEON.

2.5.2 Execution platform

The execution platform for GNATforLEON based programs is the XtratuM hypervisor for a LEON3 computer with at least 1 MB memory. An executable file can be used as a loadable image of a partition. This image can be packed in a "xef" (XtratuM Executable File) format using the tool provided in the general XtratuM software development kit, so that it can be included as the partition image in the resident software.

The resident software can be loaded into a LEON3-based computer memory by means of appropriate tools, e.g. GRMON or `mkprom`. Once loaded, the software can be debugged by running GDB on the development computer, which communicates with the target computer by means of a communication line (e.g. serial line or Ethernet).

Programs can also be tested and debugged on the development platform using the TSIM simulator, which can be connected to GDB using a socket connection.[2]

[2]TSIM is not free software and it is not part of GNATforLEON. See `http://www.gaisler.com/` for further details.

Chapter 3

How to use GNATforLEON

3.1 Software development

In order to develop programs based on GNATforLEON/ORK+ you should perform the following activities:

1. Write the source code for the program.
2. Compile and link the program.
3. Debug the program on the development platform.
4. Debug the program on the target platform.

Only Ada programs, restricted as defined by the Ravenscar profile, are supported by GNATforLEON and ORK+:

Figure 3.1 describes the data flow for the GNATforLEON compilation system. Notice that purely sequential Ada programs do not require ORK+ support, and can be compiled using a bare-board version of GNAT.[1]

3.2 Writing Ada programs

The first step in compiling an Ada application is to write the source code for the program units that make up the application. You can use your favourite text editor for this purpose or use an IDE such as GPS, the GNAT Programming Studio.

3.2.1 Ravenscar profile restrictions

When writing your Ada application code, you should bear in mind that only the Ada subset defined by the Ravenscar profile can be used. This means that you should not use any of the following features (see appendix A for a full description of the Ravenscar profile):

- Task types and object declarations other than at the library level.
- Dynamic allocation and unchecked deallocation of protected and task objects.

[1]For details about the different version of GNAT contact Ada Core at `http://www.adacore.com`.

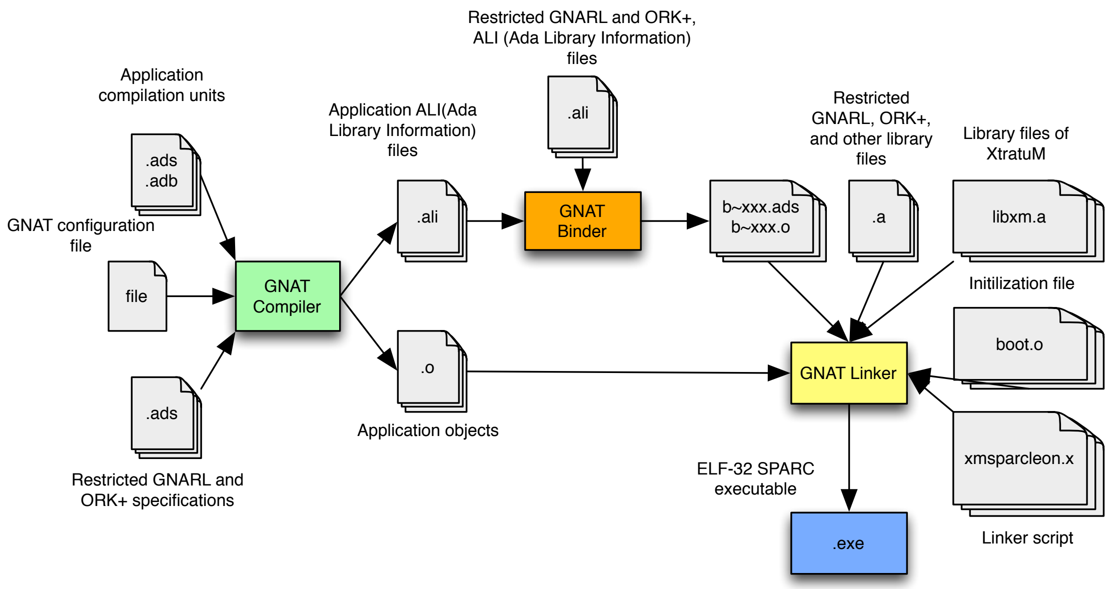

Figure 3.1: Compilation flow for GNATforLEON/ORK+ applications

- Requeue statement.
- ATC (asynchronous transfer of control via the `asynchronous_select` statement.)
- Abort statements, including `Abort_Task` in package `Ada.Task_Identification`.
- Task entries.
- Dynamic priorities.
- `Ada.Calendar` package.
- Relative delays.
- Execution-time timers and group budgets.[2]
- Non-local timing events.
- Protected types and object declarations other than at the library level.
- Protected types with more than one entry.
- Protected entries with barriers other than a single boolean variable declared within the same protected type.
- Entry calls to a protected entry with a call already queued.
- Asynchronous task control.
- All forms of `select` statements.

[2] As an exception to the Ravenscar profile, ORK+ supports one execution-time timer per task and group budgets.

- User-defined task attributes.
- Dynamically attached interrupt handlers.
- Task termination.

If your program has strong integrity requirements, you may also wish to restrict some of the sequential constructs of Ada as well (see the ALRM, ISO/IEC, b for guidelines on the Ada features you may wish to limit).

GNATforLEON assumes that the following restrictions are also applicable to your program:

- No allocators (this means that there are no `new` statements). This is required as GNATforLEON supports only static storage.
- No `Ada.Text_IO` package. This is required as ORK+ does not directly support any input-output device but a serial output line, which is not accessible through `Ada.Text_IO`.

Notice that the above restrictions are common in embedded systems and do not impose any additional limitation on what could be considered as common practice.

Warning 3.1 *GNATforLEON/ORK+ users are recommended to assign distinct priorities to all tasks and protected objects.*[3]

3.2.2 The GNAT configuration file

Configuration pragmas are put in a special source file called `gnat.adc` (see the *GNAT Reference Guide*, GNATUG). You can have GNAT check all the above restrictions for you by compiling the program with a Ravenscar configuration pragma, as shown in the following template:

Listing 3.1: Sample gnat.adc file

```
-- gnat.adc - minimum configuration file template for the Ravenscar profile
pragma Profile (Ravenscar);

-- Any other configuration pragma can be included here
```

A copy of this file is included in the `examples` directory for your convenience.[4]

Appendix A describes the Ravenscar Profile and the set of equivalent pragmas to `pragma Profile (Ravenscar)`. Notice that the following restrictions must be removed if you want to use the ORK+ extended functionality:

```
No_Dependence => Ada.Execution_Time.Group_Budget,
```

[3] GNATforLEON/ORK+ allows priorities to be shared —as long as it is compatible with the *ceiling locking* policy—, but this is not a commendable practice unless the task and protected object population exceeds the allowable range of priorities. See section 4.5 on how to configure the range of priorities and the maximum number of tasks.

[4] The directory `examples` is located directly under the directory where you have installed the `gnatforleon` distribution (`/usr/local/gnatforleon` in a standard installation).

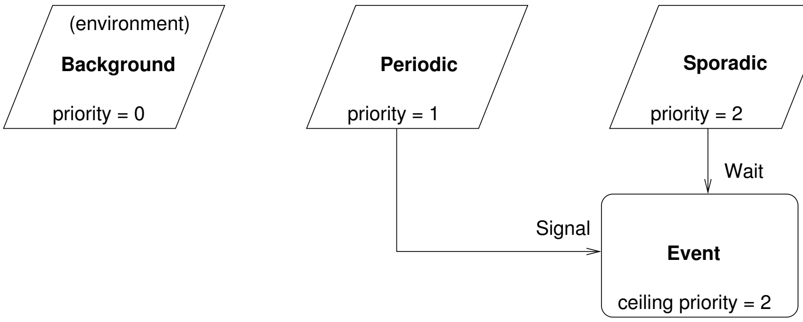

Figure 3.2: Task structure of the `hello` program (see 3.2.3). Parallelograms represent tasks, and rounded rectangles represent protected objects. The arrows denote procedure or entry calls.

```
No_Dependence => Ada.Execution_Time.Timers,
```

Of course, you should add any additional restrictions you would like to enforce on your program.

3.2.3 A first example

Let us now see a simple Ravenscar-compliant Ada program. The program consists of two compilation units: the main procedure (file `hello.adb`), and a package with all the application code, including two tasks, a protected object, and a background procedure (files `tasking.ads` and `tasking.adb`). Notice that GNAT requires that each compilation unit is in a separate file with the same name as the unit (see the *GNAT User's Guide*, GNATUG, for the details). Figure 3.2 shows the task structure of the program.

The main procedure code is provided in listing 3.2.

Listing 3.2: Main procedure of the `hello` program.

```
-- hello.adb - Main procedure for the 'hello' example
with Tasking;
-- used for Background
procedure Hello is
   pragma Priority (0);
begin
   -- do some background work - must not terminate
   Tasking.Background;
end Hello;
```

Notice that the main procedure does nothing but start a background procedure. The `Priority` pragma specifies the lowest possible priority for the environment task

(i.e. the initial task that does all initialization and then calls the main procedure). In this way, we ensure that the background procedure is only executed when there are no other executable tasks.

The environment task is not allowed to terminate in GNAT when the pragma Profile (Ravenscar) is in place. In order to prevent this to happen, the background procedure must never return. This is checked at compile time by writing a No_Return pragma near the procedure specification (in file `tasking.ads`, see listing 3.3).

Listing 3.3: Specification of the `Tasking` package.

```
-- tasking.ads - application tasks for the 'hello' example
package Tasking is
   procedure Background;
   pragma No_Return (Background);
   -- background activity - does not terminate
end Tasking;
```

The Tasking package specification contains no other declarations. All the application activities are included in the package body (listing 3.4).

Listing 3.4: Body of the `Tasking` package.

```
-- tasking.adb - application tasks for the 'hello' example
with Ada.Real_Time;
-- used for Clock, Time_Span, Milliseconds
with System.BB.Serial_Output; use System.BB.Serial_Output;
-- used for Put_Line;
package body Tasking is
   use Ada.Real_Time;

   -- Task and protected object declarations --
   type Cycle_Count is mod 10;

   task Periodic is
      pragma Priority (1);
   end Periodic;

   task Sporadic is
      pragma Priority (2);
   end Sporadic;

   protected Event is
      pragma Priority (2);
      procedure Signal (C : Cycle_Count);
      entry     Wait   (C : out Cycle_Count);
   private
      Occurred : Boolean     := False;
      Cycle    : Cycle_Count := 0;
```

```
end Event;



-- Background procedure

procedure Background is
   C : Cycle_Count := 0;
begin
   loop
      C := C + 1;
   end loop;
end Background;

-- Task and protected object bodies

task body Periodic is
   Period  : Time_Span := Milliseconds (1_000);  -- 1s
   Next    : Time := Clock;
   Cycle   : Cycle_Count := 1;
begin
   loop
      delay until Next;
      Put_Line("Hello periodic");
      if Cycle = 0 then
         Event.Signal(Cycle);       -- signal once every 10s
      end if;
      Cycle := Cycle + 1;
      Next := Next + Period;
   end loop;
end Periodic;

task body Sporadic is
   Cycle : Cycle_Count;
begin
   loop
      Event.Wait(Cycle);
      Put_Line("Hello sporadic");
   end loop;
end Sporadic;

protected body Event is

   procedure Signal (C: Cycle_Count) is
   begin
      Occurred := True;
      Cycle    := C;
```

```
      end Signal;




      entry Wait(C : out Cycle_Count)
         when Occurred is
      begin
         Occurred := False;
         C        := Cycle;
      end Wait;

   end Event;

end Tasking;
```

Notice that the background procedure actually does nothing but increment a count in an endless loop. In real applications it might include some useful work to be executed at the lowest priority.

The Tasking package contains two tasks: a periodic task, and a sporadic task. The latter is activated by the periodic task by means of a synchronization protected object (Event). This is a common way to implement software-activated sporadic tasks (Burns and Wellings, 2001). The periodic task activates the sporadic task once every ten cycles. Each task writes a string to the serial output every time it is activated.

There is a copy of the above files in the `examples/hello` distribution directory. In order to compile and link the example files, you should copy them to a working directory and follow the steps that are described in the next section.

3.3 Compiling and linking Ada programs

You can compile and link your program with `gnatmake` with the appropriate linker options for the XtratuM hypervisor. For instance:

```
$sparc-elf-gnatmake hello_world -largs boot.o traps.o std_c.o \
-nostartfiles -T xmsparcleon.x -lxm -L"directory_of_XtratuM_library"
```

The command line switches are described in the *GNAT User's Guide* (GNATUG). You can also compile, bind, and link separately:

```
$ sparc-elf-gcc -c hello.adb
$ sparc-elf-gcc -c tasking.adb
$ sparc-elf-gnatbind -x hello.ali
$ sparc-elf-gnatlink hello.ali boot.o traps.o std_c.o \
-nostartfiles -T xmsparcleon.x -lxm -L"directory_of_XtratuM_library"
```

See the *GNAT User's Guide* (GNATUG) for details on the switches and library files.

A link diagnostic information file with the symbols which are mapped by the linker together with information on global common storage allocation can be obtained by using the following switch for `gnatlink`:

```
$ sparc-elf-gnatmake -g hello -largs boot.o traps.o std_c.o \
-nostartfiles -T xmsparcleon.x -lxm -L"directory_of_XtratuM_library" \
-Wl,-Map=hello.map
```

As a result, a link diagnostic file called `hello.map` is created. This kind of map files tend to be useful in embedded software development.

After all these compilation steps an ELF-32 SPARC executable called `hello` is obtained. That file can be used as a loadable image of a XtratuM partition.

3.4 Creating and running an XtratuM partition

That first example is included in the distribution together with a proper `Makefile` for compiling, linking and creating an XtratuM executable. In other to do that, `gnatforleon` binaries must be placed in the search path in addition to the binaries for compiling XtratuM:

```
$export PATH=desired_location/SW/sparc-linux-3.4.4/bin:$PATH
$export PATH=desired_location/SW/gnatforleon-xtratum-3/bin/:$PATH
```

After that, the demo application can be built issuing the `Makefile`:

```
$make
```

The following output will be shown:

```
sparc-linux-gcc -Wall -O2 -D__ASSEMBLY__ -fno-builtin -Dsparcv8
-I../../libxm/include -nostdlib -nostdinc --include xm_inc/config.h
-o boot.o -c boot.S
sparc-elf-gnatmake -g -f hello -o partition1 -largs -nostartfiles
boot.o ../common/traps.o ../common/std_c.o -T xmsparcleon.x -lxm
-L../../libxm
sparc-elf-gcc -c -g hello.adb
hello.adb:2:06: warning: "System.BB.Serial_Output" is an internal
GNAT unit
hello.adb:2:06: warning: use of this unit is non-portable and
version-dependent
sparc-elf-gnatbind -x hello.ali
sparc-elf-gnatlink hello.ali -g -o partition1 -nostartfiles boot.o
../common/traps.o ../common/std_c.o -T xmsparcleon.x -lxm
-L../../libxm
```

After these steps a loadable image called `partition1` is created. Then the XtratuM tools are used to build a loadable image.

```
xmeformat build -c partition1 -o partition1.xef
d1deb2fe475364dd8118e94051d3c8cb partition1.xef
xmcparser -o xm_cf.bin.xmc xm_cf.sparcv8.xml
. desired_location/SW/xm-src_v3/xmconfig ;
${TARGET_CC} ${TARGET_CFLAGS_ARCH} -x c -O2 -Wall
-I${XTRATUM_PATH}/user/libxm/include -I${XTRATUM_PATH}/include
-nostdlib -nostdinc --include xm_inc/config.h --include
xm_inc/arch/arch_types.h a.c.xmc -o xm_cf.bin.xmc -Wl,--entry=0x0,
-TldsuwdTin
xmeformat build -c -m xm_cf.bin.xmc -o xm_cf.xef.xmc
7c298c56a15d106564d42e82f038b996 xm_cf.xef.xmc
xmpack check xm_cf.xef.xmc -h desired_location/SW/xm-src_v3/
core/xm_core.xef:xm_cf.xef.xmc -p 0:partition1.xef
> desired_location/SW/xm-src_v3/core/xm_core.xef ... ok
> partition1.xef ... ok
xmpack build -h
desired_location/SW/xm-src_v3/core/xm_core.xef:xm_cf.xef.xmc
-p 0:partition1.xef container.bin
> desired_location/SW/xm-src_v3/core/xm_core.xef ... ok
> partition1.xef ... ok
rswbuild container.bin resident_sw

Created by "jzamora" on "guayacan" at "Tue␣Jan␣␣8␣11:57:23␣CET␣2013"
XM path: "desired_location/SW/xm-src_v3"

XtratuM Core:
   Version: "3"
   Arch:    "sparcv8"
   File:    "desired_location/SW/xm-src_v3/core/xm_core.xef"
   Sha1:    "d86ff578c30145a1016950521f80c85558d62572"
   Changed: ""

XtratuM Library:
   Version: "3"
   File:    "desired_location/SW/xm-src_v3/user/libxm/libxm.a"
   Sha1:    "bf230e9ce58b7bdb6e4d23f1003c38417bf30cdc"
   Changed: ""

XtratuM Tools:
   File:    "desired_location/SW/xm-src_v3/user/bin/xmcparser"
   Sha1:    "e1f2dac3c4e42b87dcd422e12c73a66480da7368"
```

This produces the ELF-32 SPARC executable `resident_sw`.

3.5 Running and debugging Ada programs on the development platform

The simplest way you can test your program is by using a LEON3 simulator on your development platform. If you have the TSIM simulator[5] you can do:

```
$ tsim-leon3 -mmu resident_sw
```

And typing "go" from the command prompt you will get the following output:

```
[RSW] Start Resident Software
[RSW] Starting XM at 0x40001000
XM Hypervisor (3)
Detected 50.0MHz processor.
>> HWClocks [LEON clock (1000Khz)]
>> HwTimer [LEON timer (1000Khz)]
1 Partition(s) created
P0 ("Partition1":0) flags: [ SYSTEM FP ]:
    [0x40080000:0x40080000 - 0x4037ffff:0x4037ffff] flags: 0x200
Hello periodic
Hello periodic
Hello periodic
Hello periodic
Hello periodic
Hello periodic
Hello periodic
Hello periodic
Hello periodic
Hello periodic
Hello sporadic
Hello periodic
...
```

Running the program on TSIM by itself does not provide enough information on the behaviour of the program. You can have a better view of the program execution by using the GDB debugger, connected to the TSIM LEON simulator. In this case, TSIM must be started with the `-gdb` option, so that it waits for a connection from GDB:

```
$ tsim-leon3 -mmu -gdb
   ...
gdb interface: using port 1234
```

After that, GDB can be started in the usual way (for instance, in another window). Before loading the program to debug, GDB must be connected to the simulator (using the `extended-remote` target):

[5] TSIM is not free software, and it is not part of GNATforLEON. See `http://www.gaisler.com/`for futher details.

```
$ sparc-elf-gdb resident_sw
(gdb) target extended-remote 127.0.0.1:1234
     ...
(gdb) load
      ...
(gdb) cont
       ...
(gdb) detach
      ...
```

For a complete description of GDB commands, see the document *Debugging with GDB* (Stallman and Pessch, 2007). You can have a better view with the graphical source-level front-end to GDB of the GNAT Programming Studio (GPS).

3.6 Interrupt handlers

3.6.1 Protected procedure handlers

The Ravenscar profile allows the use of protected procedures as interrupt handlers. Interrupt handlers are declared as parameterless protected procedures, attached to an interrupt source. Interrupt sources are identified in the Ada.Interrupts.Names package. This package contains the identifiers of all the XtratuM for LEON3 interrupts.

A general template is shown in listing 3.5.

Listing 3.5: Template for interrupt handlers.

```ada
with Ada.Interrupt.Names; use Ada.Interrupt.Names;
-- used for External_Interrupt_0 , External_Interrupt_0_Priority

protected Interrupt is

   -- public protected operations

private
   -- the handler need not be visible outside the protected object
   pragma Interrupt_Priority ( External_Interrupt_0_Priority );
   procedure Handler;
   pragma Attach_Handler (Handler, External_Interrupt_0 );
   -- other private operations and data
end Interrupt;
```

Notice that you should assign a ceiling priority to the protected object with a pragma Interrupt_Priority. You should use a priority level equal or greater than the priority of the interrupt source. However, there is only one value within the Interrupt_Priority'Range for the case of ORK+ for XtratuM as it is customary for Ada run-time based on operating systems.

Warning 3.2 *You should only use priorities in the* Interrupt_Priority *range for protected objects that contain interrupt handlers (ALRM C.3.1).*

3.6.2 An example with interrupts

Appendix B describes an example application with interrupt handlers.

Chapter 4

GNATforLEON/ORK+ reference

4.1 Installation and directory structure

4.1.1 Getting GNATforLEON and ORK+

GNATforLEON/ORK+ is distributed via:

`http://www.dit.upm.es/ork/`

The sources used to build the GNATforLEON cross-compilation system can be also found at the same location. The GNATforLEON distribution includes:

`gnatforleon-2.3.0-xtratum-3-i686-pc-linux-gnu-bin.tgz` : gzipped tarfile which contains the binary distribution for GNU/Linux. The current distribution has been built on Ubuntu 12.04. However, it runs on most modern Linux distributions. In order to avoid problems with different versions of `libc`, binaries are statically linked.

`gnatforleon-2.3.0-xtratum-3-src.tgz` : gzipped tarfile which contains the sources as well as the procedures for building the GNATforLEON.

`examples-2.3.0-xtratum-3.tgz` : gzipped tarfile which contains some examples of the GNATforLEON functionality. The example described in section 3.2.3 as well as the demo application described in appendix B together with some examples of inter-partition communication are included.

4.1.2 Installing GNATforLEON

The GNAT directory tree has been compiled to reside in any directory. After obtaining the gzipped tarfile `gnatforleon-2.3.0-xtratum-3-i686-pc-linux-gnu-bin.tgz`, which includes the binary distribution, uncompress and untar it in the desired location.

The GNATforLEON distribution can be installed with the following commands (assuming the gzipped tar file is in directory `/tmp`):

```
$ tar -zxvf gnatforleon-2.3.0-xtratum-3-i686-pc-linux-gnu-bin.tgz\
-C desired_location
```

After the cross-compilation system is installed, the directory `desired_location/gnatforleon-2.3.0/bin/` must be added to the search path (usually, environment variable `PATH` in your shell).

4.1.3 Installing the GNATforLEON sources

In the following, the installation directory for source files is assumed to be `/usr/local/gnatforleon/src`, although they can be installed at any other location as well. After obtaining the gzipped tarfile `gnatforleon-2.3.0-xtratum-3-src.tgz`, which contains the sources of the GNATforLEON cross-compilation system, uncompress and untar it to `/usr/local/gnatforleon/src`.

The GNATforLEON distribution can be installed with the following commands (assuming the gzipped tar file is in `/tmp/gnatforleon-2.3.0-xtratum-3-src`):

```
$ cd /usr/local
$ tar -zxvf /tmp/gnatforleon-2.3.0-xtratum-3-src.tgz
```

The sources have been adapted using AdaCore patches and specific GNATforLEON patches. These sources are ready to build GNATforLEON CCS. The source distribution contains procedures (`Makefile`) for building the whole GNATforLEON CCS and the GNATforLEON `adalib` (see sections 4.5 and 4.5.3).

4.1.4 Directory structure

Contents of `/usr/local/gnatforleon`

- `bin`: executables.
- `info`: gcc documentation in info format.
- `lib`: gcc libraries which include GNATforLEON adalib for XtratuM/LEON3 target.
- `libexec`: gcc libraries.
- `man`: man pages.
- `sparc-elf`: newlib (libc) library for SPARC family.

Contents of `/usr/local/gnatforleon/src`

- `binutils-2.16.1`: Adapted sources of binutils for GNATforLEON.
- `newlib-1.14.0`: Adapted sources of newlib for GNATforLEON.
- gmp-4.2.2: Sources of library for arbitrary precision arithmetic.
- mpc-0.8: Sources of library for the arithmetic of complex numbers.
- mpfr-2.3.1: Sources of library for multiple-precision floating-point computations.
- `gcc-4.5`: Adapted sources of gcc for GNATforLEON.

- `gcc-4.5/gcc/ada`: Adapted sources of GNAT GPL 2011for GNATforLEON including GNATforLEON itself.
- `gdb-7.2`: Adapted sources of gdb for GNATforLEON.

4.1.5 Tools

GNATforLEON includes the following tools in the `/usr/local/gnatforleon/bin` directory:

- `sparc-elf-addr2line`: utility to translate program addresses into file names and line numbers.
- `sparc-elf-ar`: library archiver.
- `sparc-elf-as`: cross-assembler.
- `sparc-elf-c++filt`: utility to demangle C++ symbols.
- `sparc-elf-gcc`: C cross-compiler.
- `sparc-elf-gccbug`: a tool for reporting GCC Bugs.
- `sparc-elf-gcov`: coverage testing tool.
- `sparc-elf-gdb`: the GNU Debugger.
- `sparc-elf-gnat`: utility to list GNAT commands, qualifiers and options.
- `sparc-elf-gnatbind`: Ada binder.
- `sparc-elf-gnatchop`: Ada source code splitter.
- `sparc-elf-gnatfind`: Ada utility for locating definitions and/or references to a specified entity or entities.
- `sparc-elf-gnatkr`: Ada file name kruncher.
- `sparc-elf-gnatlink`: Ada linker.
- `sparc-elf-gnatls`: Ada library lister.
- `sparc-elf-gnatmake`: Ada make utility.
- `sparc-elf-gnatprep`: Ada pre-processor.
- `sparc-elf-gnatxref`: Ada utility to generating a full report of all cross-references.
- `sparc-elf-ld`: linker.
- `sparc-elf-nm`: utility to print symbol table.
- `sparc-elf-objcopy`: utility to convert between binary formats.
- `sparc-elf-objdump`: utility to dump various parts of executables.

- `sparc-elf-ranlib`: library sorter.
- `sparc-elf-size`: utility to display segment sizes.
- `sparc-elf-strings`: utility to dump strings from executables.
- `sparc-elf-strip`: utility to remove symbol table.

4.1.6 Documentation

Extensive documentation for all the tools can be found in the the `/usr/local/gnatforleon/info` and `/usr/local/gnatforleon/man` directories.

Documentation for the XtratuM hypervisor can be found at the FentISS site located at http://www.xtratum.org. Documentation for the LEON3 processor can be found at the Aeroflex Gaisler site located at `http://www.gaisler.com`.

4.2 Kernel interface

4.2.1 Introduction

The ORK+ kernel provides all the required functionality to support real-time programming on top of the XtratuM facilities and the LEON3 hardware architecture. The kernel functions are grouped as follows:

1. Task management, including task creation, synchronization, and scheduling.
2. Time services, including absolute delays and real-time clock.
3. Interrupt handling.

All these functions are described in the following subsections.

The kernel is normally used as a low-level layer providing the basic functionality to the upper GNAT run-time system. However, it can be used directly from an application program, written in either Ada or C.

4.2.2 Threads and synchronization

The operations related with the initialization of the kernel, thread management, synchronization, and scheduling are implemented in the package System.BB.Threads :

Listing 4.1: Specification of System.BB.Threads.

```
-- Package that implements basic tasking functionalities

pragma Restrictions (No_Elaboration_Code);

with System;
-- Used for Address
--          Null_Address
```

```
--             Any_Priority

with System.Parameters;
-- Used for Size_Type

with System.BB.CPU_Primitives;
-- Used for Context_Buffer

with System.BB.Time;
-- Used for Time

with System.BB.Interrupts;
-- Used for Interrupt_Set
--             Empty_Interrupt_Set

package System.BB.Threads is
   pragma Preelaborate;

   --------------------------
   -- Basic thread support --
   --------------------------

   type Thread_Descriptor;
   -- This type contains the information about a thread

   type Thread_Id is access all Thread_Descriptor;
   -- Type used as thread identifier

   Null_Thread_Id : constant Thread_Id := null;
   pragma Export (C, Null_Thread_Id, "system_bb_null_thread_id");
   -- Identifier used to define an invalid value for a thread identifier

   type Thread_States is (Runnable, Suspended, Delayed);
   -- These are the three possible states for a thread under the Ravenscar
   -- profile restrictions: Runnable (not blocked, and it may also be
   -- executing), Suspended (waiting on an entry call), and Delayed (waiting
   -- on a delay until statement).

   type Exec_Handler is access procedure (I : Integer);

   type Thread_Descriptor is record
      Context : aliased System.BB.CPU_Primitives.Context_Buffer;
      -- Location where the hardware registers (stack pointer, program
      -- counter, ...) are stored. This field supports context switches among
      -- threads.

      ATCB : System.Address;
      -- Address of the Ada Task Control Block corresponding to the Ada task
```

```
-- that executes on this thread.

 Base_Priority  : System.Any_Priority;
-- Base priority of the thread

 Active_Priority  : System.Any_Priority;
pragma Volatile ( Active_Priority );
-- Active priority that differs from the base priority due to dynamic
--  priority changes required by the Ceiling Priority Protocol. This
--  field is marked as Volatile for a fast implementation of
--  Get_Priority.

Top_Of_Stack : System.Address;
-- Address of the top of the stack that is used by the thread

Bottom_Of_Stack : System.Address;
-- Address of the bottom of the stack that is used by the thread

Next : Thread_Id;
-- Points to the ready thread that is in the next position for
-- execution.

Alarm_Time : System.BB.Time.Time;
-- Time (absolute) when the alarm for this thread expires

Next_Alarm : Thread_Id;
-- Next thread in the alarm queue. The queue is ordered by expiration
-- times. The first place is occupied by the thread which must be
--  first awaken.

State : Thread_States;
-- Encodes some basic information about the state of a thread

Wakeup_Signaled : Boolean;
-- Variable which reflects whether another thread has performed a
-- Wakeup operation on the thread.

 Time_Init_Execution  : System.BB.Time.Time;
-- Time when task has received the CPU
Execution_Time       : System.BB.Time.Time;
-- Execution Time of the task
Time_Remaining       : System.BB.Time.Time;
-- Time remaining of timer associated to the task
Is_Timer_Alarm       : Boolean;
-- Flag that indicates if it has been put an alarm associated to the
-- timer associated to the task
Is_GB_Alarm          : Boolean;
-- Flag that indicates if it has been put an alarm associated to the
```

```
      -- timer associated to the group of the task
      TM_Integer          : Integer;
      -- Index to the array with the handlers associated to the timers
      Time_Diff           : System.BB.Time.Time;
      -- Difference of time between time of the init of the execution of the
      -- task and the asignation of the timer to the task
      Time_Diff_GB        : System.BB.Time.Time;
      -- Difference of time between time of the init of the execution of the
      -- task and the asignation of the timer to the group of the task
      Handler             : Exec_Handler;
      -- Handler associated to the Execution_Time Timer of the task
      GB_Id               : Integer;
      -- Identifier associated to the Group_Budget of the task
      GB_Index            : Integer;
      -- Place of the array associated to the Group_Budget where the task
      -- data is stored
      Handler_GB          : Exec_Handler;
      -- Handler associated to the Group_Budget of the task
   end record;

   for Thread_Descriptor use
      record
         Context at 0 range 0 ..
           (System.BB.CPU_Primitives.Context_Buffer_Size - 1);
      end record;
   -- It is important that the Context field is placed at the beginning of
   -- the record, because this assumption is using for implementing context
   -- switching.

   procedure Initialize
     (Environment_Thread : Thread_Id;
      Main_Priority      : System.Any_Priority);
   -- Procedure to initialize the board and the data structures related to
   -- the low level tasking system. This procedure must be called before any
   -- other tasking operation.

   procedure Thread_Create
     (Id            : Thread_Id;
      Code          : System.Address;
      Arg           : System.Address;
      Priority      : System.Any_Priority;
      Stack_Address : System.Address;
      Stack_Size    : System.Parameters.Size_Type);
   pragma Export (C, Thread_Create, "system_bb_thread_create");
   -- Create a new thread
   --
   -- The new thread executes the code at address Code and using Args
   -- as argument. Priority is the base priority of the new
```

```ada
-- thread. The new thread is provided with a stack of size
-- Stack_Size that has been preallocated at Stack_Address.
--
-- A procedure to destroy threads is not available because that is not
-- allowed by the Ravenscar profile .

function Thread_Self return Thread_Id;
pragma Inline (Thread_Self);
pragma Export (C, Thread_Self, "system_bb_thread_self");
-- Return the thread identifier of the calling thread

----------------
-- Scheduling --
----------------

procedure Set_Priority (Priority : System.Any_Priority);
pragma Inline (Set_Priority);
pragma Export (C, Set_Priority, "system_bb_set_priority");
-- Set the active priority of the executing thread to the given value

function Get_Priority (Id : Thread_Id) return System.Any_Priority;
pragma Inline (Get_Priority);
pragma Export (C, Get_Priority, "system_bb_get_priority");
-- Get the current active priority of any thread

procedure Sleep;
pragma Export (C, Sleep, "system_bb_sleep");
-- The calling thread is unconditionally suspended

procedure Wakeup (Id : Thread_Id);
pragma Export (C, Wakeup, "system_bb_wakeup");
-- Thread Id becomes ready (the thread must be previously suspended)

----------
-- ATCB --
----------

procedure Set_ATCB (ATCB : System.Address);
pragma Inline (Set_ATCB);
-- This procedure sets the ATCB passed as argument for the
-- currently running thread.

function Get_ATCB return System.Address;
pragma Inline (Get_ATCB);
-- Returns the ATCB of the currently executing thread

---------------------------------
-- Execution_Time functions ---
```

```
-------------------------------------
type Handler is access protected procedure (I : Integer);

Global_TM_Pointer : Integer := 1;

Global_GB_Pointer : Integer := 1;
Budget_Array : array (1 .. 255) of System.BB.Time.Time_Span;

function Get_Timer_Id return Integer;
function Get_GB_Id return Integer;

------------------------------
-- Timing_Events types --
------------------------------

Global_TE_Pointer : Integer := 1;
function Get_TE_Id return Integer;

type TE_Alarm_Queue;
-- This type contains the time of alarms relative of Timing Events and
-- the next alarm.

type TE_Alarm_Queue_Id is access all TE_Alarm_Queue;
-- Type used as TE_Alarm_Queue identifier

Null_TE_Alarm_Queue_Id : constant TE_Alarm_Queue_Id := null;

type TE_Alarm_Queue is record
   Previous_Alarm : TE_Alarm_Queue_Id  := Null_TE_Alarm_Queue_Id;
   Alarm_Time     : System.BB.Time.Time := System.BB.Time.Time'Last;
   TE_Id          : Integer            := 0;
   Next_Alarm     : TE_Alarm_Queue_Id  := Null_TE_Alarm_Queue_Id;
end record;

end System.BB.Threads;
```

Before calling any kernel operation, the initialization routine (Initialize) must be explicitly invoked. Its purpose is to initialize the ready queue, as well as the descriptors of the environment thread (which executes the main procedure) and the dummy thread (which is executed when there is no ready thread in the system).

Once the kernel has been initialized, threads can be created invoking the procedure Thread_Create. This procedure needs to know the pointer to the function to execute (and its argument), its priority, and its required stack size. With this information a new thread is created. Both the thread descriptor and the new stack for the thread are obtained from a preallocated pool, so that no dynamic memory allocation is needed. The function Thread_Self is used to obtain the identity of the currently running thread.

The base priority of the thread, which is the priority of the thread without taking into account the dynamic priority changes which may be caused by the Ceiling_Locking policy, can be changed by calling the procedure Set_Priority . The current base priority of a thread can be obtained calling the procedure Get_Priority .

The synchronization of threads is usually achieved using condition variables. However, the Ravenscar Profile disallows complex synchronization patterns and two simple procedures are enough for supporting that simpler synchronization pattern. The procedure Sleep unconditionally suspends the current thread. As a result, the currently executing thread will leave the CPU. The procedure Wakeup makes a previously suspended thread become ready. The thread will be inserted at the tail of its active priority so that the thread will resume execution.

Scheduling of threads is performed according to the FIFO_Within_Priorities and Ceiling_Locking policies (see ALRM D.2-3).

4.2.3 Time management

The operations related with time are implemented in package System.BB.Time.

Listing 4.2: Specification of System.BB.Time.

```
-- Package in charge of implementing clock and timer functionalities

pragma Restrictions (No_Elaboration_Code);

with System.BB.Peripherals;
-- Used for Clock_Freq_Hz

package System.BB.Time is
   pragma Preelaborate;

   type Time is mod 2 ** 64;
   for Time'Size use 64;
   -- XTRATUM PORT
   -- Time represent the number of microseconds

   type Time_Span is range -2 ** 63 .. 2 ** 63 - 1;
   for Time_Span'Size use 64;
   -- Time_Span represents the length of time intervals , and it is
   -- defined as a 64-bit signed integer .

   ----------------
   -- Constants --
   ----------------
   Time_Span_Zero : constant Time_Span := 0;

   Tick : constant := 1;
   -- A clock tick is a real time interval during which the clock value (as
   -- observed by calling the Clock function) remains constant. Tick is the
```

```
-- average length of such intervals.

-- Number of ticks per second
Ticks_Per_Second : constant := 10**6;

---------------------
-- Initialization --
---------------------

procedure Initialize_Timers;
-- Initialize this package (clock and alarm handlers). Must be called
-- before any other functions.

-----------------
-- Operations --
-----------------

function Number_Of_Ticks_Per_Second return Time;
pragma Export (C, Number_Of_Ticks_Per_Second, "system_bb_ticks_per_second");
-- Get the number of ticks (or clock interrupts) per second

function Clock return Time;
pragma Export (C, Clock, "system_bb_clock");
-- Get the number of ticks elapsed since startup

function Partition_Clock return Time;
pragma Export (C, Partition_Clock, "system_bb_partition_clock");
-- Get the number of ticks of the executed partition
-- elapsed since startup.

procedure Delay_Until (T : Time);
pragma Export (C, Delay_Until, "system_bb_delay_until");
-- Suspend the calling thread until the absolute time specified by T

function "+" (Left : Time; Right : Time_Span) return Time;

function Get_Pending_Alarm return Boolean;
-- Returns Pending_Alarm variable

function Get_Pending_Partition_Alarm return Boolean;
-- Return Pending_Partition_Alarm variable

procedure Turn_True_Pending_Alarm;
-- Turns Pending_Alarm variable to true

procedure Turn_True_Pending_Partition_Alarm;
-- Turns Pending_Partition_Alarm variable to true
```

```
procedure Inmediate_Alarm (Now : in out System.BB.Time.Time);

procedure Inmediate_Partition_Alarm (Now : in out System.BB.Time.Time);

end System.BB.Time;
```

ORK+ provides direct support for the Ravenscar profile time services, i.e. Ada.Real_Time.Clock, absolute delays, global timing events, and execution-time clocks. It also supports execution-time timers and group budgets, as an extension to the Ravenscar profile. The original implementation of these time services is based on two hardware timers: a periodic timer and a single-shot timer (Urueña et al., 2007).

It must be noted that hardware timers are indeed elapsed-time timers. However, the XtratuM hypervisor, as it is common in partitioned systems, has a dual concept of time: in addition to the common notion of elapsed real-time, there is the notion of *partition-time*, which only advances when a partition is scheduled. Accordingly, Xtratum provides two kinds of software timers, as well as two kinds of clocks: elapsed-time clocks and timers, and partition-time clocks and timers.

The real-time mechanisms, i.e. Ada.Real_Time.Clock, absolute delays, and global timing events, are implemented in ORK+/XtratuM in a similar way to the bare machine version, i.e. by using the elapsed-time clock and timer. However, execution-time clocks cannot be implemented in the same way. Since the hypervisor switches the running partition without giving any notice to the software running in the partitions, implementing execution-time clocks on elapsed-time timers would also account for the time the partition is not running. In order to avoid this inconvenience, all execution-time mechanisms, i.e. execution-time clocks and timers, as well as group budgets, are implemented using partition time timers.

Time is represented in the ORK+ kernel as a 64-bit integer number of ticks. A tick is a real time interval during which the clock value (as observed by calling the System.BB.Clock function) remains constant. The number of ticks per second can be read from the constant called Ticks_Per_Second. The XtratuM hypervisor provides both notions of time with a microsecond resolution. Therefore, tick is equal to one microsecond for ORK+/Xtratum.

The current value of the real-time clock can be obtained calling function Clock. This function returns the number of ticks elapsed since system startup, providing a time zone independent, monotonically increasing, absolute time value.

When a thread needs to be suspended until an absolute time, the procedure Delay_Until is called. The effect of this call is the suspension of the calling thread until the value of the clock is equal to or greater than the specified time. If the alarm time is not in the future, the ownership of the processor is transferred to the next ready thread with the currently active priority.

There is also a function Partition_Clock that gives support for execution-time clocks. As well as subprograms that provide for execution-time timers, group budgets, and timing events.

4.2.4 Interrupt handling

Interrupt operations are declared in the package System.BB.Interrupts.

Listing 4.3: Specification of System.BB.Interrupts.

```
-- Package in charge of implementing the basic routines for interrupt
-- management.

pragma Restrictions (No_Elaboration_Code);

with System;
-- Used for Any_Priority

with System.BB.Parameters;
-- Used for Interrupt_Levels

with System.BB.Peripherals;
-- Used for Priority_Of_Interrupt

package System.BB.Interrupts is
   pragma Preelaborate;

   Max_Interrupt : constant := System.BB.Parameters.Interrupt_Levels;
   -- The interrupts are distinguished by its interrupt level

   subtype Interrupt_ID is Natural range 0 .. Max_Interrupt;
   -- Interrupt identifier

   No_Interrupt : constant Interrupt_ID := 0;
   -- Special value indicating no interrupt

   type Interrupt_Handler is access procedure (Id : Interrupt_ID);
   -- Prototype of procedures used as low level handlers

   procedure Initialize_Interrupts;
   -- Initialize table containing the pointers to the different interrupt
   -- stacks. Should be called before any other subprograms in this package.

   procedure Attach_Handler
     (Handler : Interrupt_Handler;
      Id      : Interrupt_ID);
   pragma Inline (Attach_Handler);
   pragma Export (C, Attach_Handler, "system_bb_attach_interrupt_handler");
   -- Attach the procedure Handler as handler of the interrupt Id

   function Priority_Of_Interrupt
     (Id : Interrupt_ID) return System.Any_Priority
   renames
     System.BB.Peripherals.Priority_Of_Interrupt;
   -- This function returns the software priority associated to the interrupt
   -- given as argument.
```

```
function Current_Interrupt return Interrupt_ID ;
pragma Inline ( Current_Interrupt );
-- Function that returns the hardware interrupt currently being
-- handled ( if any). In case no hardware interrupt is being handled
-- the returned value is No_Interrupt .

function Within_Interrupt_Stack
  (Stack_Address : System.Address) return Boolean;
pragma Inline ( Within_Interrupt_Stack );
-- Function that tells whether the Address passed as argument belongs to
-- the interrupt stack that is currently being used ( if any). It returns
-- True if Stack_Address is within the range of the interrupt stack being
-- used. In case Stack_Address is not within the interrupt stack (or no
-- interrupt is being handled)

end System.BB.Interrupts;
```

Notice that XtratuM virtualizes the 16 interrupt sources of the SPARC architecture, and defines 32 additional virtual interrupt sources that are intended to be used for Xtratum services. Moreover, XtratuM does not support priorities for interrupt sources. Therefore, all the interrupt sources have the same priority, as it is customary for hypervisor and operating systems.

Interrupt handlers are always executed using an interrupt stack. The size of the interrupt stack can be modified by the user changing the value of System.BB.Parameters.Interrupt_Stack_Size. Interrupt handlers are called directly from the XtratuM virtual interrupt sources, and are executed as if they were directly invoked by the interrupted thread (but using the interrupt stack).

The procedure Attach_Handler must be called to attach a handler to an interrupt. The required arguments for this procedure are:

- Handler. The address of the procedure used as interrupt handler.
- Id. The interrupt identifier.

If the active priority of a running thread is equal to or greater than the one of virtual interrupts, the virtual interrupt will not be processed. However, the virtual interrupt will remain pending until the active priority of the running task becomes lower than the priority of interrupts, and only then will the interrupt be processed.

An important implication of this interrupt model is that users should always use distinct priorities for threads and virtual interrupt handlers; otherwise, tasks could delay the virtual interrupt handling. The implication of this (correct and important) recommendation is that the user should not assign priorities in the Interrupt_Priority range to software tasks.

4.3 Errors

Errors in the kernel are signalled to the application program by means of the Ada exception mechanism.

4.4 Run-time considerations

Storage allocation

Dynamic storage should only be allocated (from a preallocated pool) during the initialization of the kernel, as a result of task creation (ATCBs, stacks, ...). If the preallocated pool is completely full, any request for new space raises Tasking_Error.

Interrupt priorities

When attaching protected procedures to virtual interrupts, the ceiling priority of the protected object should be carefully chosen. The compiler checks that the ceiling priority of the protected object is in the range of System. Interrupt_Priority . This range of priorities is mapped to one interrupt level provided by the XtratuM hypervisor. Therefore, when assigning priorities to protected objects that contain protected procedure handlers, the priority value must be equal to the priority of virtual interrupts. Otherwise, the execution of the program is erroneous (ALRM C.3.1).

Potentially blocking operations

Pragma Profile (Ravenscar) includes the pragma Detect_Blocking. Therefore, the exception Program_Error will be raised whenever this kind of bounded error is detected.

Potentially blocking operations are (ALRM 9.5.1):

- Protected entry calls;
- delay until ;
- Ada.Synchronous_Task_Control.Suspend_Until_True (ALRM D.10);

An external call on a protected subprogram with the same target object as that of the protected action, or a call on a subprogram whose body contains a potentially blocking operation is also a blocking operation (ALRM 9.5.1).

4.5 Tailoring the kernel

ORK+ can be tailored to different applications by means of configuration parameters. Paarmeters are declared in System.BB.Parameters (file `s-bbpara-xtratum.ads`). This file, as well as other ORK+ files, can be found in the `gcc-4.5/gcc/ada` directory.

You can modify this file and rebuild the whole cross-compilation system in order to build a GNATforLEON kernel that satisfies your requirements.

It is recommended that the file `s-bbpara-xtratum.ads` be previously compiled with the same flags which will be later used to compile the whole run-time library:

```
$ sparc-elf-gcc -c -gnatpg s-bbpara-xtratum.ads
```

After updating `s-bbpara-xtratum.ads`, the GNATforLEON cross-compilation system can be rebuilt from the sources (see section 4.5.3).

4.5.1 Configurable parameters

The configurable parameters included in the System.BB.Parameters package are:

- Interrupt_Stack_Size : Size of the interrupt stack.
- Clock_Frequency: Frequency of the LEON3 processor.

It is also possible to configure the priority ranges by modifying the file `system-xi-sparc-full.ads` and then rebuilding the cross-compilation system.

The configurable parameters which define the memory region by the system integrator to the ORK+ partition are included in the linker script file `xmsparcleon.x`, which can be found in the directory within the examples. You can edit that file and change the `RAM_SIZE` and `RAM_SIZE` values to fit in the assigned memory region. There is no need to rebuild the GNATforLEON cross-compilation system when this parameter is changed but just to link again the partition.

The maximum number of tasks is not configurable. The number of tasks is limited by the task stack size and the amount of storage available. As the storage space needed for tasks is allocated at compilation time, if there is not enough memory a linker error message will be output.

4.5.2 Interrupt names

The virtual interrupt names have been defined in ORK+ as close as possible to the names given in the XtratuM reference manual (Masmano et al., 2011).

The ORK+ interrupt names are defined in System.BB.Peripherals. These names are available to GNARL by appropriate renames in the GNULL package System.OS_Interface. The standard Ada package Ada.Interrupts.Names contains the virtual interrupt names available for Ada applications.

Listing 4.4: Specification of Ada.Interrupts.Names.

```
with Ada.Interrupts;

with System.OS_Interface;

package Ada.Interrupts.Names is

   --------------------------
   -- External Interrupts --
   --------------------------

    External_Interrupt_3 : constant Interrupt_ID :=
      Interrupt_ID (System.OS_Interface.External_Interrupt_3);
     External_Interrupt_3_Priority : constant System.Interrupt_Priority :=
      System.OS_Interface.External_Interrupt_3_Priority;

    External_Interrupt_2 : constant Interrupt_ID :=
      Interrupt_ID (System.OS_Interface.External_Interrupt_2);
     External_Interrupt_2_Priority : constant System.Interrupt_Priority :=
```

```
    System.OS_Interface.  External_Interrupt_2_Priority  ;

  External_Interrupt_1  : constant Interrupt_ID :=
    Interrupt_ID  (System.OS_Interface. External_Interrupt_1 );
   External_Interrupt_1_Priority   : constant System. Interrupt_Priority  :=
    System.OS_Interface.  External_Interrupt_1_Priority  ;

  External_Interrupt_0  : constant Interrupt_ID :=
    Interrupt_ID  (System.OS_Interface. External_Interrupt_0 );
   External_Interrupt_0_Priority   : constant System. Interrupt_Priority  :=
    System.OS_Interface.  External_Interrupt_0_Priority  ;

-----------------------
-- Timers Interrupts --
-----------------------

Timer_2 : constant Interrupt_ID :=
   Interrupt_ID  (System.OS_Interface.Timer_2);
 Timer_2_Priority  : constant System. Interrupt_Priority  :=
   System.OS_Interface. Timer_2_Priority ;

Timer_1 : constant Interrupt_ID :=
   Interrupt_ID  (System.OS_Interface.Timer_1);
 Timer_1_Priority  : constant System. Interrupt_Priority  :=
   System.OS_Interface. Timer_1_Priority ;

-------------------------------
-- Extended Interrupts       --
-------------------------------

Watchdog_Timer : constant Interrupt_ID :=
   Interrupt_ID  (System.OS_Interface.Watchdog_Timer);
Watchdog_Timer_Priority : constant System. Interrupt_Priority  :=
   System.OS_Interface.Watchdog_Timer_Priority;

Shutdown : constant Interrupt_ID :=
   Interrupt_ID  (System.OS_Interface.Shutdown);
Shutdown_Priority  : constant System. Interrupt_Priority  :=
   System.OS_Interface.Shutdown_Priority;

Sampling_Port : constant Interrupt_ID :=
   Interrupt_ID  (System.OS_Interface.Sampling_Port);
 Sampling_Port_Priority  : constant System. Interrupt_Priority  :=
   System.OS_Interface. Sampling_Port_Priority ;

Queuing_Port : constant Interrupt_ID :=
   Interrupt_ID  (System.OS_Interface.Queuing_Port);
 Queuing_Port_Priority  : constant System. Interrupt_Priority  :=
```

```
      System.OS_Interface.Queuing_Port_Priority;

   Cyclic_Slot_Start : constant Interrupt_ID :=
      Interrupt_ID (System.OS_Interface.Cyclic_Slot_Start);
   Cyclic_Slot_Start_Priority : constant System.Interrupt_Priority :=
      System.OS_Interface.Cyclic_Slot_Start_Priority;

   Mem_Protect : constant Interrupt_ID :=
      Interrupt_ID (System.OS_Interface.Mem_Protect);
   Mem_Protect_Priority : constant System.Interrupt_Priority :=
      System.OS_Interface.Mem_Protect_Priority;

   ---------------------
   -- UART Interrupts --
   ---------------------

   UART_1_RX_TX : constant Interrupt_ID :=
      Interrupt_ID (System.OS_Interface.UART_1_RX_TX);
   UART_1_RX_TX_Priority : constant System.Interrupt_Priority :=
      System.OS_Interface.UART_1_RX_TX_Priority;

   UART_2_RX_TX : constant Interrupt_ID :=
      Interrupt_ID (System.OS_Interface.UART_2_RX_TX);
   UART_2_RX_TX_Priority : constant System.Interrupt_Priority :=
      System.OS_Interface.UART_2_RX_TX_Priority;

   ------------------------------
   -- Miscelaneous Interrupts --
   ------------------------------

   Correctable_Error_In_Memory : constant Interrupt_ID :=
      Interrupt_ID (System.OS_Interface.Correctable_Error_In_Memory);
   Correctable_Error_In_Memory_Priority : constant System.Interrupt_Priority :=
      System.OS_Interface.Correctable_Error_In_Memory_Priority;

   DSU : constant Interrupt_ID :=
      Interrupt_ID (System.OS_Interface.DSU);
   DSU_Priority : constant System.Interrupt_Priority :=
      System.OS_Interface.DSU_Priority;

   PCI : constant Interrupt_ID :=
      Interrupt_ID (System.OS_Interface.PCI);
   PCI_Priority : constant System.Interrupt_Priority :=
      System.OS_Interface.PCI_Priority;

end Ada.Interrupts.Names;
```

4.5.3 Compiling the kernel

Procedures for rebuilding the whole GNATforLEON cross-compilation system and adapting GNATforLEON are the in `/usr/local/gnatforleon/src` directory.

In order to rebuild the whole GNATforLEON cross-compilation system, you need to do the following:

1. Edit the file `Makefile` in order to change GNATforLEON default installation directory (`/usr/local/gnatforleon`) and set the GNATBOOT path to a valid native GNAT GPL 2011 distribution.

2. Type:

   ```
   $ make
   ```

The procedure will take about 10-15 minutes on a modern computer. On successful execution, the GNATforLEON cross-compilation system will be installed.

Since this procedure takes a long time, it is possible to selectively rebuild only the GNATforLEON `adalib`. However, GNATforLEON must have been previously compiled in order to do this.

If the GNATforLEON cross-compilation system has been built previously, the subdirectories called `tmp-gcc-4.1.3-build` must already exist in `/usr/local/gnatforleon/src`. It is then possible to rebuild only the GNATforLEON `adalib` by typing

```
$ make adalib
```

in the `/usr/local/gnatforleon/src` directory.

Warning 4.1 *You will need a native GNAT GPL 2011 distribution installed on your computer in order to rebuild or adapt GNATforLEON 2.3.0.*

Appendix A

The Ravenscar profile

A.1 Introduction

The Ravenscar Profile is the best known result of the *8th International Real-Time Ada Workshop (IRTAW'8)*, which was held in April 1997 in Ravenscar, Yorkshire (Baker and Vardanega, 1997; Burns and Wellings, 1997; Burns et al., 1998). The purpose of the profile is to identify a subset of the tasking features of Ada which can be implemented using a small, reliable kernel. The expected benefits of this approach are:

- Improved memory and execution time efficiency, by removing features with a high overhead.
- Improved reliability, by removing non-deterministic and non analysable features.
- Improved timing analysis, by removing non-deterministic and non-analysable features.

The profile was revised at subsequent meetings, including IRTAW'9 (Asplund et al., 1999), IRTAW'10 (Wellings, 2001), IRTAW'11 (Burns and Brosgol, 2002), and IRTAW'12 (Dobbing and de la Puente, 2003). It is included in the ISO report *Guide for the use of the Ada Programming Language in High Integrity Systems* (HIS) (ISO/IEC, b), and in the current Ada standard (ARM05). The summary presented here is based on the *Guide for the use of the Ada Ravenscar Profile in High Integrity Systems* (ISO/IEC, a), with a few changes to adapt it to the Ada 2005 standard.

The definition of the Ravenscar profile is based on Ada, including the Systems Programming and Real-Time annexes (ARM05, annexes C & D). It only addresses tasking constructs, as the reliability aspects of the sequential part of Ada are covered in other sections of the HIS report (ISO/IEC, b).

The profile is based on a computation model with the following features:

- A single processor.
- A fixed number of tasks.
- A single invocation event for each task. The invocation event may be generated by the passing of time (for time-triggered tasks) or by a signal from either another task or the environment (for sporadic tasks).

- Task interaction only by means of shared data with mutually exclusive access.

This set of features effectively supports building systems with the following kinds of components:

- Periodic tasks.
- Program driven sporadic tasks.
- Interrupt driven sporadic tasks.
- Protected objects implementing shared data (typically with no entries).
- Protected objects for event synchronization (with at most one entry called by a single signalling task).

These components are considered to be expressive enough for implementing high integrity systems for space applications on a single processor.

A.2 Definition

The Ravenscar profile is defined by the following restrictions (ISO/IEC, a):

A.2.1 Forbidden features

RP1 Task types and object declarations other than at the library level. Thus, there is no hierarchy of tasks.

RP2 Dynamic allocation and unchecked deallocation of protected and task objects.

RP3 Requeue.

RP4 ATC (asynchronous transfer of control via the asynchronous_select statement.)

RP5 Abort statements, including Abort_Task in package Ada. Task_Identification .

RP6 Task entries.

RP7 Dynamic priorities.

RP8 Ada.Calendar package.

RP9 Relative delays.

RP10 Protected types and object declarations other than at the library level.

RP11 Protected types with more than one entry.

RP12 Protected entries with barriers other than a single boolean variable declared within the same protected type.

RP13 An entry call to a protected entry with a call already queued.

RP14 Asynchronous task control.

RP15 All forms of select statements.

RP16 User-defined task attributes.

RP17 Dynamic interrupt handler attachments.

RP18 Task termination.

RP19 Specific termination handlers.

RP20 Local timing events.

RP21 Execution-time timers.

RP22 Group budgets.

A.2.2 Supported features

The above restrictions still support a wide range of tasking features, such as:

RP23 Task objects, restricted as above.

RP24 Protected objects, restricted as above.

RP25 Atomic and Volatile pragmas.

RP26 Delay until statements.

RP27 Ceiling_Locking policy and FIFO_within_priorities dispatching.

RP28 Count attribute (but not within entry barriers).

RP29 Task identifiers, e.g. T'Identity, E'Caller.

RP30 Synchronous task control.

RP31 Task discriminants.

RP32 Ada.Real_Time package.

RP33 Protected procedures as statically bound interrupt handlers.

RP34 Execution-time clocks declared at library level.

RP35 A global fall-back handler.

A.2.3 Dynamic semantics

Some aspects of the profile require their dynamic semantics to be defined:

RP36 If an entry call is made on an entry that already has a queued call (i.e. the queue length would become 2), then Program_Error is raised.

RP37 It is implementation-defined what happens if a task attempts to terminate. A global fall-back handler (see ARM05, C.7.3) can be set for the environment task. The handler is called whenever a task attempts to terminate.

RP38 If a task executes a potentially blocking operation from within a protected object then Program_Error must be raised.

A.3 Denoting the restrictions

The run-time profile Ravenscar can be enforced with the following pragma:

```
pragma Profile(Ravenscar);
```

which is equivalent to the following set of pragmas:

```
pragma Task_Dispatching_Policy ( FIFO_Within_Priorities );

pragma Locking_Policy ( Ceiling_Locking );

pragma Detect_Blocking;

pragma Restrictions (

    No_Abort_Statements,
    No_Dynamic_Attachment,
    No_Dynamic_Priorities,
    No_Implicit_Heap_Allocations ,
    No_Local_Protected_Objects,
    No_Local_Timing_Events,
    No_Protected_Type_Allocators,
    No_Relative_Delay,
    No_Requeue_Statements,
    No_Select_Statements,
    No_Specific_Termination_Handlers ,
    No_Task_Allocators,
    No_Task_Hierarchy,
    No_Task_Termination,
    Simple_Barriers ,
    Max_Entry_Queue_Length => 1,
    Max_Protected_Entries => 1,
    Max_Task_Entries => 0,
    No_Dependence => Ada.Asynchronous_Task_Control,
    No_Dependence => Ada.Calendar,
    No_Dependence => Ada.Execution_Time.Group_Budget,
    No_Dependence => Ada.Execution_Time.Timers,
    No_Dependence => Ada.Task_Attributes);
```

A.4 Extended profile

ORK+ supports the following features which are not allowed in the Ravenscar profile:

XP01 One execution-time timer per task, declared at the library level.

XP02 Group budgets. Task groups must be static and declared at the library level.

Notice that using pragma Profile (Ravenscar) in your program will make the compiler report the use of execution-time timers and group budgets as incorrect. If you need to use the extended features you should provide the full set of pragmas and restrictions listed in A.3 above, except for the two restrictions on Ada.Execution_Time .Group_Budget and Ada.Execution_Time.Timers.

Appendix B

Example program

B.1 Description

The goal of this example is to show the functionality of GNATforLEON.

The example program has three tasks which spend their computation time calling the Whetstone benchmark. This benchmark performs floating point operations developed for the Performance Issues Working Group (PIWG) test suite.

In order to exercise communication among tasks, two of the three tasks interact through a protected object. One task is sporadic and the other is periodic. The third task is an independent periodic task.

The sporadic task is activated by a virtual interrupt for which it waits on an protected entry with a simple boolean barrier. A protected procedure is used to handle the interrupt, in accordance with the GNATforLEON interrupt model. The protected procedure opens the barrier and then the sporadic task becomes runnable. After the task executes its code the barrier is closed again.

A periodic task activates the virtual interrupt. XtratuM has special functionality which allows the user to force virtual interrupts by software. Such functionality is used by the periodic task to activate the virtual interrupt at regular intervals.

All the tasks print the value of `Real_Time.Clock` whenever they start and finish executing their body. Only absolute delays and the monotonic clock of the `Real_Time` package are used. In order to avoid undesirable interactions between input-output and task scheduling, the special `Put` operation of the `System.IO` package is used.

The example program is designed to cover all the features which are needed in space embedded applications. In particular, the example includes:

- Task management
- Task synchronization
- Time keeping and absolute delays
- Ada interrupt management
- Floating point calculations

B.2 Temporal requirements of the tasks

Figure B.1 shows the structure of the task set. The task set will be analysed for the temporal requirements of the tasks as shown in table B.1. The period for task A is interpreted as a minimum inter-arrival time.

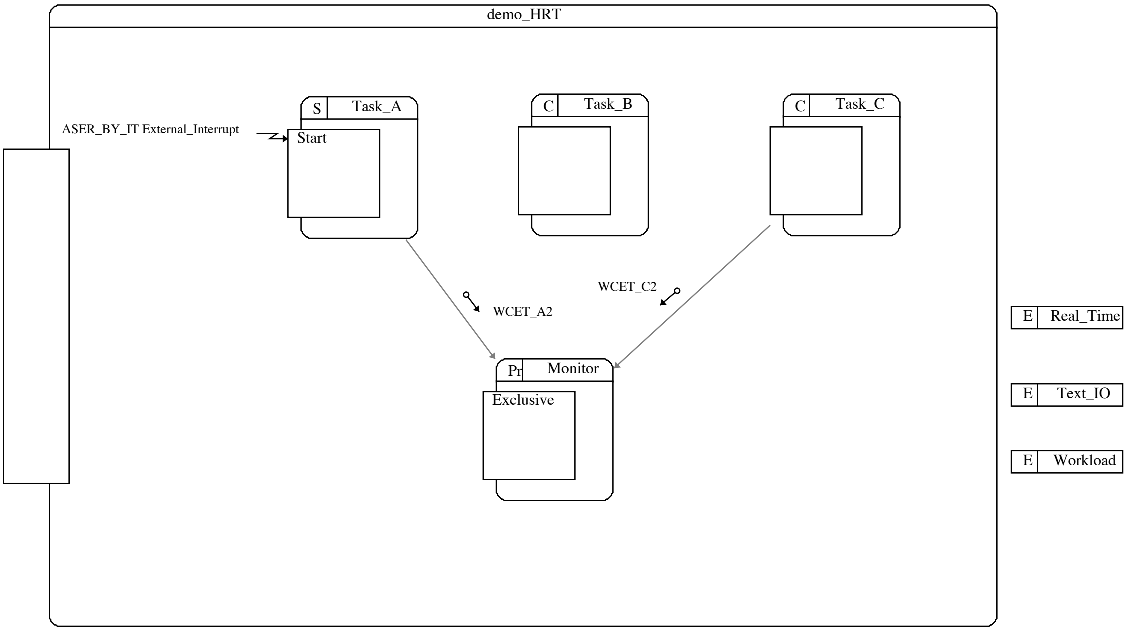

Figure B.1: Example task set

Task	Period	Activities
A	14	a_1, a_2
B	20	b_1
C	36	c_1, c_2

Table B.1: Temporal requirements of the example tasks

Tasks A and C contain two logical blocks of activities, while task B has only one. Activity a_1 corresponds to internal computation of task A, and a_2 to the execution time of task A inside resource `Monitor`. Similarly, c_1 corresponds to the internal execution time of task C, and c_2 to the execution time of task C inside resource `Monitor`. Finally, b_1 corresponds to the whole execution of task B. By extension, the same set of symbols denote the WCET of the corresponding block of activity.

Table B.2 shows the priorities assigned to the tasks. Task A has the highest priority, task C has the lowest priority, task B has a medium priority.

B.3 Schedulability analysis

The Ravenscar profile includes `pragma Task_Dispatching_Policy (FIFO_Within_Priorities)` and `pragma Locking_Policy (Ceiling_Locking)` (see appendix A).

Task (block)	Priority	WCET	Resource
A(a_1)	Priority'Last	1	None
A(a_2)	Priority'Last	2	Monitor
B (b_1)	Priority'Last - 1	6	None
C (c_1)	Priority'Last - 2	2	None
C (c_2)	Priority'Last	6	Monitor

Table B.2: Priority assignment and Worst Case Execution Time of activities

Therefore, the maximum response time of every task can be evaluated using equation B.1.

$$R_i = C_i + B_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{T_j} \right\rceil \times C_j \tag{B.1}$$

Which is solved using a recurrence relation:

$$w_i^{n+1} = C_i + B_i + \sum_{j \in hp(i)} \left\lceil \frac{w_i^n}{T_j} \right\rceil \times C_j$$

As immediate ceiling locking is used, the maximum blocking time can be evaluated for every task.

Task A: can suffer a blocking time equal to WCET of activity c_2, i.e. $B_a = 6$.

Task B: can suffer a blocking time equal to WCET of activity c_2, i.e. $B_b = 6$.

Task C: is the lowest priority task and so can not suffer blocking, i.e. $B_c = 0$.

The maximum response time of every task can now be calculated. The minimum inter-arrival time will be used as the period in order to calculate the worst case response time for the low priority task.

Following common practice, an initial value w_i^0 equal to the sum of the WCET of higher priority task plus the WCET of the task itself is used:

$$w_a^1 = 3 + 6 = 9$$

$$\begin{aligned} w_b^1 &= 6 + 6 + \left\lceil \frac{9}{14} \right\rceil \times 3 = 15 \\ w_b^2 &= 6 + 6 + \left\lceil \frac{15}{14} \right\rceil \times 3 = 18 \\ w_b^3 &= 6 + 6 + \left\lceil \frac{18}{14} \right\rceil \times 3 = 18 \end{aligned}$$

$$\begin{aligned} w_c^1 &= 8 + \left\lceil \frac{17}{14} \right\rceil \times 3 + \left\lceil \frac{17}{20} \right\rceil \times 6 = 20 \\ w_c^2 &= 8 + \left\lceil \frac{20}{14} \right\rceil \times 3 + \left\lceil \frac{20}{20} \right\rceil \times 6 = 20 \end{aligned}$$

Figure B.2 shows the schedule of the tasks starting at time zero for 60 time units of 100ms each. Up arrows denote activation time and down arrows denote deadlines. Filled boxes denote sections executed at ceiling priority.

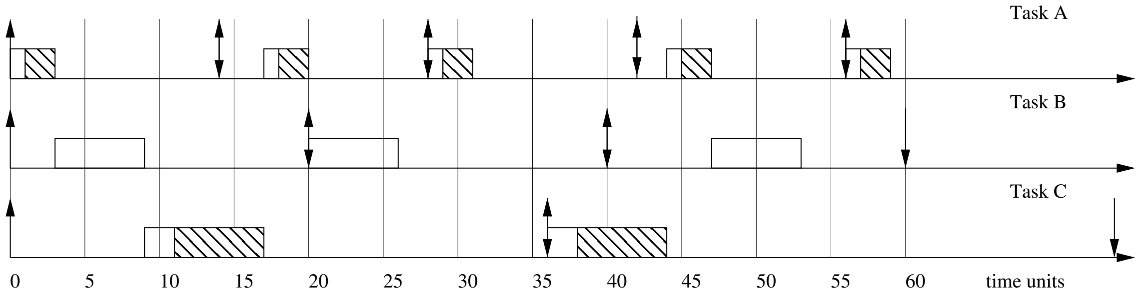

Figure B.2: Schedule of tasks

B.4 Example program output

The output of the example program shows the start and termination time of each task cycle. You can use TSIM for executing it, the options `-freq 50 -fast_uart` can be used to set the clock frequency defined in System.BB.Parameters and to set "infinite" speed in the UART channel.

With a time unit of 100ms the actual output is:[1]

```
$ tsim-leon3 -freq 50 -fast_uart -mmu resident_sw

 This TSIM evaluation version will expire March 1, 2010


 TSIM/LEON3 SPARC simulator, version 2.0.14 (evaluation version)

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serial port A on stdin/stdout
allocated 4096 K RAM memory, in 1 bank(s)
allocated 16 M SDRAM memory, in 1 bank
allocated 2048 K ROM memory
icache: 1 * 4 kbytes, 16 bytes/line (4 kbytes total)
dcache: 1 * 4 kbytes, 16 bytes/line (4 kbytes total)
section: .text, addr: 0x40380000, size 17692 bytes
section: .rodata, addr: 0x40384520, size 579 bytes
section: .container, addr: 0x4000, size 172048 bytes
section: .got, addr: 0x2e010, size 8 bytes
section: .eh_frame, addr: 0x2e018, size 64 bytes
read 42 symbols
tsim> g
resuming at 0x403811c8
[RSW] Start Resident Software
[RSW] Starting XM at 0x40001000
```

[1]The start and termination time of each task cycle can vary depending of the GNATforLEON version.

```
XM Hypervisor (3.3 r2)
Detected 50.0MHz processor.
>> HWClocks [LEON clock (1000Khz)]
>> HwTimer [LEON timer (1000Khz)]
1 Partition(s) created
P0 ("Partition1":0) flags: [ SYSTEM FP ]:
    [0x40080000:0x40080000 - 0x4037ffff:0x4037ffff] flags: 0x200
Task A running RT.Clock = 0.000970000
Task A finishing RT.Clock = 0.296557000
Task B running RT.Clock = 0.297352000
Task B finishing RT.Clock = 0.887957000
Task C running RT.Clock = 0.888693000
Task C finishing RT.Clock = 1.680429000
Task A running RT.Clock = 1.681160000
Task A finishing RT.Clock = 1.977238000
Task B running RT.Clock = 2.000449000
Task B finishing RT.Clock = 2.591501000
Task A running RT.Clock = 2.800932000
Task A finishing RT.Clock = 3.096647000
Task C running RT.Clock = 3.600449000
Task C finishing RT.Clock = 4.392197000
Task A running RT.Clock = 4.392930000
Task A finishing RT.Clock = 4.688339000
Task B running RT.Clock = 4.689146000
Task B finishing RT.Clock = 5.280242000
Task A running RT.Clock = 5.600934000
Task A finishing RT.Clock = 5.896649000
Task B running RT.Clock = 6.000447000
Task B finishing RT.Clock = 6.591497000
Task A running RT.Clock = 7.000933000
Task A finishing RT.Clock = 7.296844000
Task C running RT.Clock = 7.297653000
Task C finishing RT.Clock = 8.089246000
Task B running RT.Clock = 8.089976000
Task A running RT.Clock = 8.400964000
Task A finishing RT.Clock = 8.696658000
Task B finishing RT.Clock = 8.978672000
       ...
```

There are small variations with respect to the timetable of figure B.2 which are due to:

1. Kernel overhead.

2. The code of the tasks includes calls to the Whetstone benchmark with an actual parameter which suits the WCET defined in table B.2. As a result, the execution time of protected operations, delay settings, clock readings, and other operations increases the WCET defined in table B.2.

B.5 Example code

Listing B.1: Demo main procedure

```
with Tasks;
with System;

procedure Demo is

   pragma Priority (System. PriorityFirst );

begin

   Tasks.Background;

end Demo;
```

Listing B.2: Tasks spec ification

```
package Tasks is

   procedure Background;

end Tasks;
```

Listing B.3: Tasks body

```
with System.IO;

with Ada. Interrupts .Names;

with Ada.Real_Time;
use type Ada.Real_Time.Time_Span;

with System;
with Workload;
with  Force_External_Interrupt_2 ;

package body Tasks is

   Time_Unit : constant Ada.Real_Time.Time_Span :=
                  Ada.Real_Time. Milliseconds (100);

   -- A program for measuring this constant can be built with
   -- make -f Makefile.measure
```

```
Time_per_Kwhetstones : constant Ada.Real_Time.Time_Span :=
                       Ada.Real_Time.Nanoseconds (212_000); -- 2.3.0

procedure Execution_Time (Time : Ada.Real_Time.Time_Span) is

begin
   Workload.Small_Whetstone (Time / Time_per_Kwhetstones);
end Execution_Time;

-- 500 Milliseconds is the initial offset for the tasks
-- It is enough time to elaborate the program

Offset : constant Ada.Real_Time.Time_Span :=
         Ada.Real_Time.Milliseconds (500);

Time_Zero : constant Ada.Real_Time.Time :=
            Ada.Real_Time.Time_of (0, Ada.Real_Time.Time_Span_Zero) +
            Offset;

-- This procedure prints Real_Time.Clock - Time_Zero

procedure Print_RTClok is
   Seconds_Count_From_Time_Zero : Ada.Real_Time.Seconds_Count;
   Time_Span_From_Time_Zero : Ada.Real_Time.Time_Span;
   Duration_From_Time_Zero : Duration;

begin

   Ada.Real_Time.Split (Ada.Real_Time.Clock - Offset,
                        Seconds_Count_From_Time_Zero,
                        Time_Span_From_Time_Zero);
   Duration_From_Time_Zero := Duration (Seconds_Count_From_Time_Zero) +
                  Ada.Real_Time.To_Duration (Time_Span_From_Time_Zero);
   System.IO.Put (" RT.Clock = ");
   System.IO.Put (Duration'Image(duration_From_Time_Zero));

end Print_RTClok;

-- Temporal parameters of Tasks

subtype Tasks is character range 'A' .. 'C';

WCET_A1 : constant Ada.Real_Time.Time_Span := 1 * Time_Unit;
WCET_A2 : constant Ada.Real_Time.Time_Span := 2 * Time_Unit;
Period_A : constant Ada.Real_Time.Time_Span := 14 * Time_Unit;

WCET_B : constant Ada.Real_Time.Time_Span := 6 * Time_Unit;
```

```
   Period_B : constant Ada.Real_Time.Time_Span := 20 * Time_Unit;

   WCET_C1 : constant Ada.Real_Time.Time_Span := 2 * Time_Unit;
   WCET_C2 : constant Ada.Real_Time.Time_Span := 6 * Time_Unit;
   Period_C : constant Ada.Real_Time.Time_Span := 36 * Time_Unit;

   procedure Background is

   begin
      loop
--          Workload.Small_Whetstone (25);
--          Print_RTClok;
         null;
      end loop;
   end Background;

   task A is
      pragma Priority (System.Priority'Last);
   end A;

   task B is
      pragma Priority (System.Priority'Last - 1);
   end B;

   task C is
      pragma Priority (System.Priority'Last - 2);
   end C;

   protected Monitor is

      pragma Priority (System.Priority'Last);

      procedure Exclusive (Time : Ada.Real_Time.Time_Span;
                           Running_Task : Tasks);

   end Monitor;

   -- This task simulates a interrupt every Period_A

   task Interrupt is
      pragma Interrupt_Priority (System.Interrupt_Priority'Last);
   end Interrupt;

   protected Interrupt_Semaphore is
      pragma Priority (Ada.Interrupts.Names.External_Interrupt_2_Priority);

      -- pragma Interrupt_Priority (System.Interrupt_Priority'Last);
```

```
    entry Wait;

    procedure Signal;
    pragma Attach_Handler (Signal,
                           Ada. Interrupts .Names. External_Interrupt_2 );

private

    Signaled  :  Boolean := False;

end Interrupt_Semaphore;

protected body Interrupt_Semaphore is

    entry Wait when Signaled is

    begin
        Signaled  := False;
    end Wait;

    procedure Signal is
    begin
        Signaled  := True;
    end Signal;

end Interrupt_Semaphore;

task body Interrupt  is
    Next_Time : Ada.Real_Time.Time := Time_Zero;
begin
    loop
        delay until  Next_Time;
         Force_External_Interrupt_2  ;
        Next_Time := Next_Time + Period_A;
    end loop;
end Interrupt;

protected body Monitor is

    procedure Exclusive (Time : Ada.Real_Time.Time_Span;
                         Running_Task : Tasks) is

    begin
        Execution_Time (Time);
        System.IO.Put ("Task␣");
        System.IO.Put (Running_Task);
        System.IO.Put ("␣finishing");
        Print_RTClok;
```

```
         System.IO.New_Line;
      end Exclusive;

   end Monitor;

   task body A is
   begin
      loop
         Interrupt_Semaphore.Wait;
         System.IO.Put ("Task␣A␣running␣␣");
         Print_RTClok;
         System.IO.New_Line;
         Execution_Time (WCET_A1);
         Monitor.Exclusive (WCET_A2, 'A');
      end loop;
   end A;

   task body B is
      Next_Time : Ada.Real_Time.Time := Time_Zero;
   begin
      loop
         delay until Next_Time;
         System.IO.Put ("Task␣B␣running␣␣");
         Print_RTClok;
         System.IO.New_Line;
         Execution_Time (WCET_B);
         Next_Time := Next_Time + Period_B;
         System.IO.Put ("Task␣B␣finishing");
         Print_RTClok;
         System.IO.New_Line;
      end loop;
   end B;

   task body C is
      Next_Time : Ada.Real_Time.Time := Time_Zero;
   begin
      loop
         delay until Next_Time;
         System.IO.Put ("Task␣C␣running␣␣");
         Print_RTClok;
         System.IO.New_Line;
         Execution_Time (WCET_C1);
         Monitor.Exclusive (WCET_C2, 'C');
         Next_Time := Next_Time + Period_C;
      end loop;
   end C;
end Tasks;
```

Listing B.4: Force_External_Interrupt_2

```
with Interfaces.C;
with Ada.Interrupts.Names;
with Ada.Interrupts.Management;

procedure Force_External_Interrupt_2 is

   Error : Integer;

begin

    Error := Ada.Interrupts.Management.Unmask_IRQ
             (Ada.Interrupts.Names.External_Interrupt_2);

    Error := Ada.Interrupts.Management.Set_IRQ
             (Ada.Interrupts.Names.External_Interrupt_2);

end Force_External_Interrupt_2;
```

Listing B.5: Configuration file

```
-- gnat.adc - minimum configuration file template for the Ravenscar profile
pragma Profile (Ravenscar);

-- Any other configuration pragma can be included here
```

Appendix C

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